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Working Group 2: Report on SBN Beam Flux Systematics

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Abstract

The Booster Neutrino Beamline (BNB) produces a high purity ν_μ beam from the Fermilab 8 GeV Booster with energies in the range of 0.1 to 2 GeV. The Short Baseline Neutrino (SBN) program at Fermilab proposes to deploy several neutrino detectors at various locations within a few km from the BNB to mount a high precision search of neutrino oscillations beyond the 3-flavor νSM in both the disappearance, $\nu_\mu \to \nu_\mu$, and appearance , $\nu_\mu \to \nu_e$, modes. The neutrino detectors will be exposed to both the BNB neutrino beam as well as the NuMI beam (at large off-axis angles). A critical component of any neutrino oscillation experiment is the precision determination of the neutrino flux from the source, and its composition. This report will summarize the different techniques used by current short baseline neutrino accelerator experiments to determine the unoscillated neutrino flux, the resultant systematic uncertainties on the flux determination, and the implications for future experiments at the BNB. In addition, the report will present an optimization of the neutrino detector locations with respect to the BNB to maximize the sensitivity to neutrino oscillations beyond the current 3-flavor νSM.

Contents

1 The Fermilab Neutrino Beamlines for the SBN Program

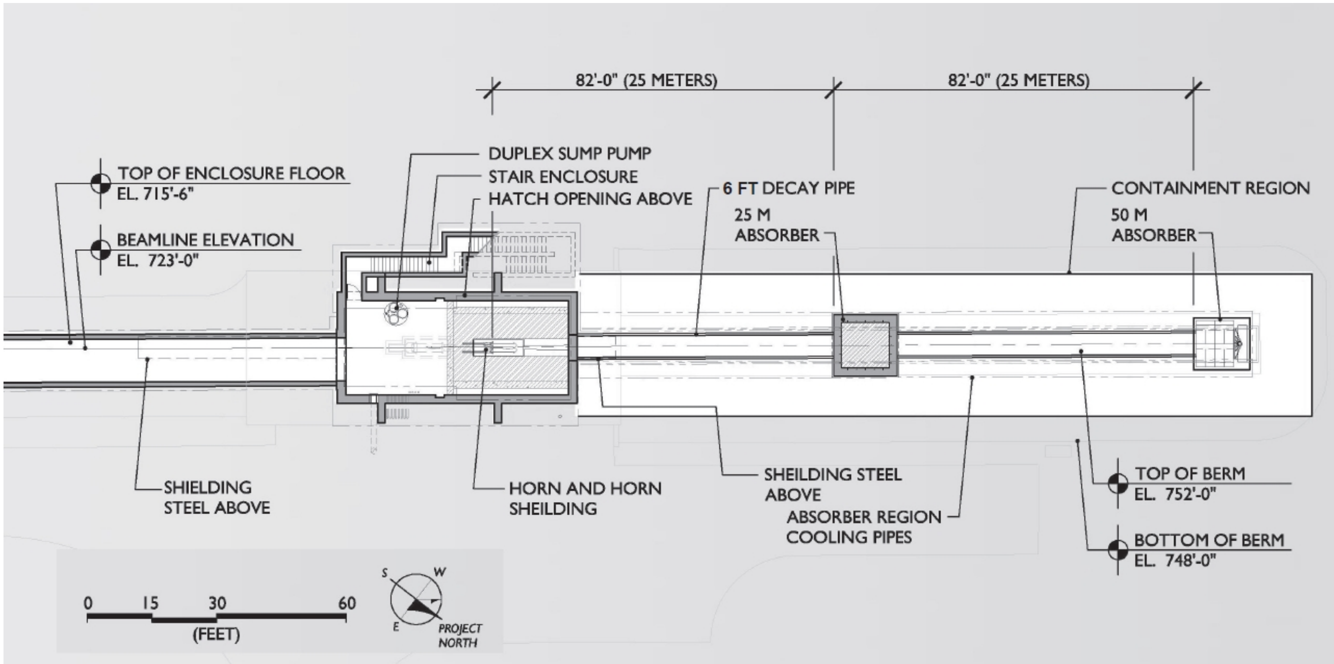


Figure 1: The Booster Neutrino Beamline

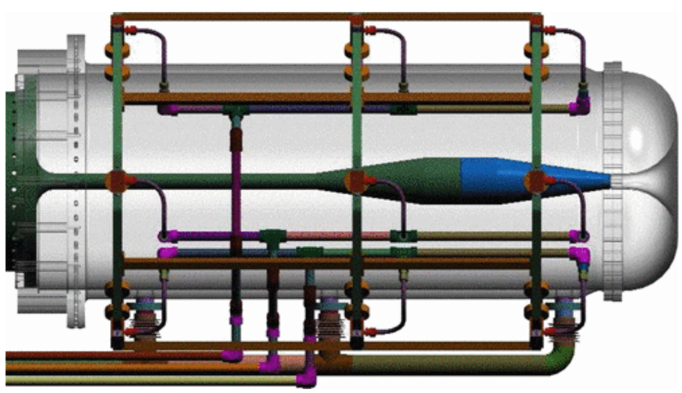


Figure 2: The Booster Neutrino Beam focusing system

A critical component of any neutrino oscillation experiment is the precision determination of the neutrino flux from the source, and its composition. There are currently two neutrino beamlines at Fermi National Accelerator Laboratory (Fermilab) in Batavia, IL: the Booster Neutrino Beamline (BNB) [1] and the Neutrinos at the Main Injector (NuMI) beamline [2]. The Short Baseline Neutrino program (SBN) will utilize neutrinos produced primarily by the BNB to search for neutrino oscillations beyond those of the current 3-flavor νSM. The MiniBooNE and MicroBooNE experiments currently situated on-axis in the BNB are both located at approximately a distance of 450m and 470m from the BNB source respectively. Both experiments are also illuminated by the NuMI beamline with an off-axis angle of 110mrad and a distance of 745m from the NuMI target. The SBN program proposes to locate an additional

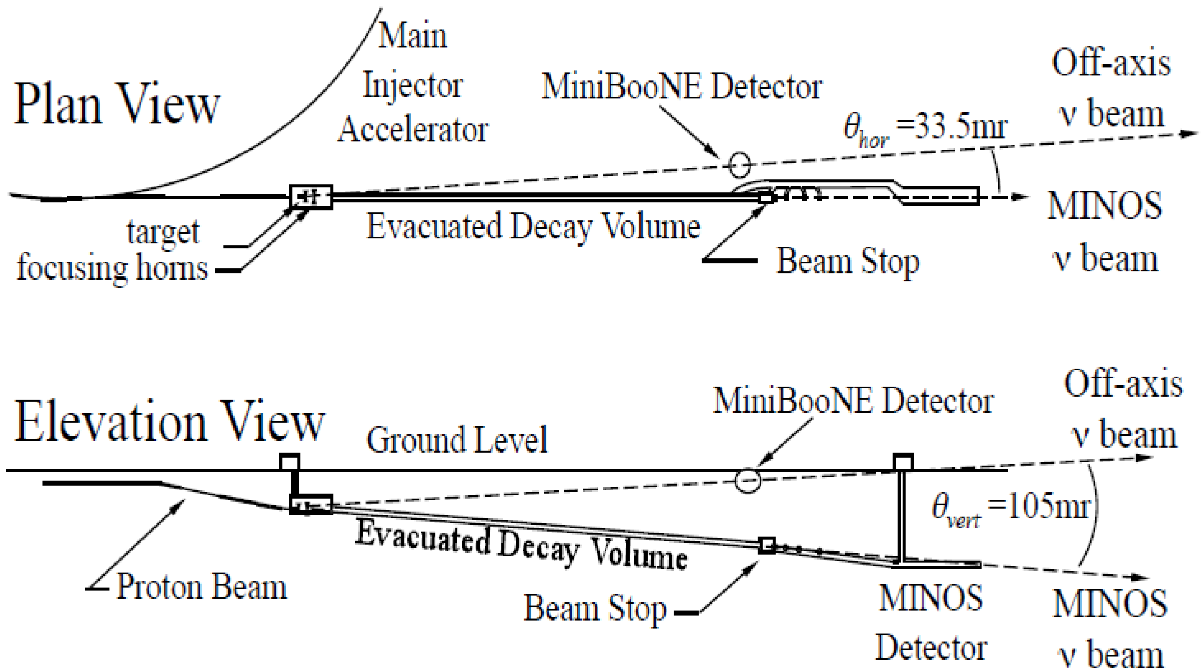


Figure 3: Location of the MiniBooNE detector in relation to the NuMI Beamline

set of Liquid-Argon Time-Projection-Chamber (LArTPC) detectors on the BNB beamline to enable a search for neutrino oscillations at several L/E locations within 1km of the BNB. In addition to the MicroBooNE detector, the SBN will comprise at least two more LAr detectors: a near detector (SBN-ND) at a location closer to the BNB source than MicroBooNE and a far detector (SBN-FD) at a distance further from MicroBooNE. The combination of SBN-ND, MicroBooNE and SBN-FD will reduce the neutrino flux uncertainties in the oscillation search. In this report, we will summarize the different techniques by which the MiniBooNE and MINOS experiments have modeled the absolute neutrino flux from the BNB and NuMI beamlines and the associated systematics uncertainties. A study of the flux uncertainties at the different candidate SBN LAr detector locations and the degree of cancelation of correlated uncertainties has been carried out in other to determine the optimal location in the BNB of the additional SBN LAr detectors.

Both the BNB and NuMI beamlines utilize proton beams incident on low-Z targets to produce charged mesons that are charge selected and focused using magnetic focusing horns. The BNB utilizes an 8 GeV proton beam from the Fermilab Booster incident on a thin Be target of length 71cm that is embedded in a single 174 kA pulsed magnetic horn. The focused mesons are allowed to decay in an air filled cylindrical region that is 3 feet in radius and 45 meters long. The resulting neutrino beam then travels through 450 meters of dirt to the MiniBooNE detector [3] which is located at a distance of 541 meters from the target. The NuMI beamline utilizes a 120 GeV proton beam incident on a thin graphite target 95cm in length. The resulting mesons are focused by two 185 kA pulsed horns placed 10 meters apart. The NuMI decay volume is He filled, 1m in radius and 675m long. The MINOS experiment [4] comprises two detectors in the NuMI beamline: a Near Detector (ND) located 1.04 km from the target and a Far Detector (FD) located 735 km from the target. The BNB and NuMI beamlines produce a neutrino flux that is more than 90% ν_μ with small contaminations of $\bar{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$. The fluxes of the different neutrino species from the BNB and NuMI beamline in the MiniBooNE and MINOS ND respectively are shown in Figure 4.

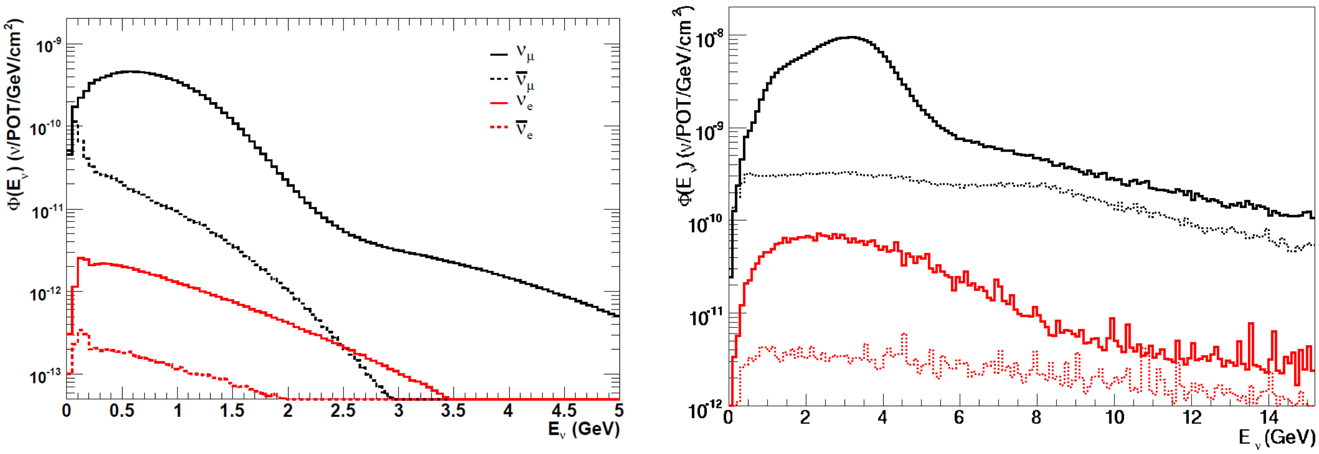


Figure 4: Neutrino beams at Fermilab. The left figure is the BNB neutrino flux at the MiniBoone detector. The right figure is the NuMI beam neutrino flux at the MINOS ND. The ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu_e}$ components are shown.

In addition to the on-axis BNB neutrinos, the MiniBooNE and MicroBooNE detectors also recieves a significant flux of off-axis neutrinos from the NuMI beamline [5]. The MiniBooNE detector is located at a distance of 745m from the NuMI target, at an off-axis angle of 110mrads. The flux of muon neutrinos in the MiniBooNE detector from NuMI and BNB is shown in Figure 5.

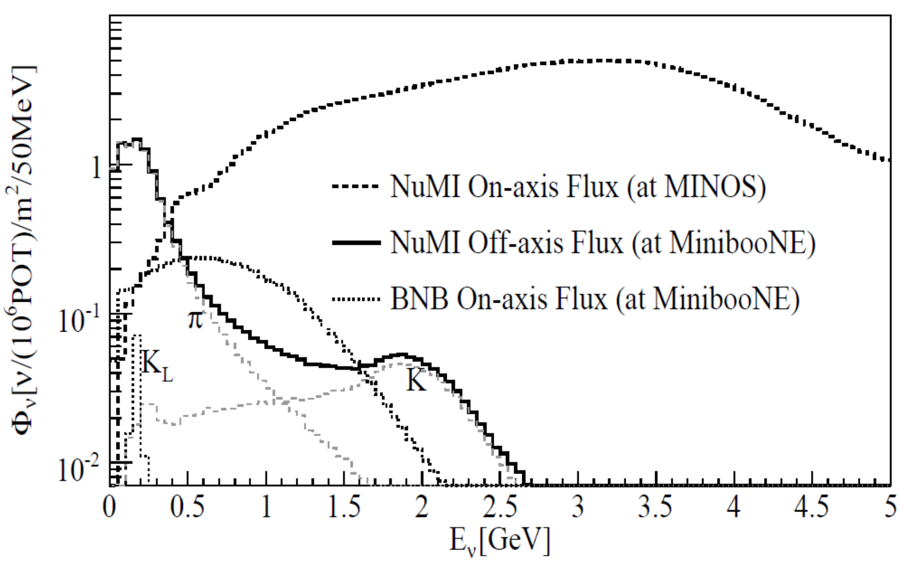


Figure 5: A comparison of the ν_μ flux in the MiniBooNE and MINOS ND from the different neutrino beamlines. The NuMI off-axis at MiniBooNE is shown as a solid line.

The current MiniBooNE and MicroBooNE experiment are short baseline neutrino oscillation experiment whose primary goal is to search for ν_μ to ν_e oscillations at large Δm^2 using baselines of order 1km. The determination of the expected ν_μ flux and the ν_e contamination in MiniBooNE from the BNB beam was obtained from a detailed simulation of the beamline using GEANT4 [6] tuned using external measurements of hadron production cross-sections in the target and beamline elements. The MINOS experiment is a long baseline two-detector neutrino oscillation experiment. The determination of the neutrino flux in the MINOS Far Detector was obtained from a FLUKA 08 [7]/GEANT4 simulation of the beamline which is tuned to match the observed neutrino interaction rate in the Near Detector using the technique described in [8, 4]. The NuMI simulation tuned to match the on-axis higher energy neutrino rate in the MINOS ND is then used to predict the off-axis NuMI ν_μ rate observed in the MiniBooNE detector.

The BNB and NuMI focusing horns can operate in reversed polarity to produce a $\bar{\nu}_\mu$ beam. This enables the SBN experiments to study neutrino and anti-neutrino oscillations in the same experiment.

2 BNB Absolute Neutrino Flux Predictions and Systematics

The MiniBooNE experiment has carried out a detailed modeling of the BNB neutrino beamline. To simulate the interaction of the primary 8 GeV Booster proton beam with the Be target and secondary interactions in the Al horn, the MiniBooNE experiment uses custom tables describing the double differential cross-sections for the production of protons, neutrons, pions and Kaon as a function of p_z and p_T based on external measurements [9]. As discussed in [9], the existing external measurements of pion and Kaon production from p-Be interactions cover the same kinematic regions in x_F and p_T as the BNB mesons that contribute to the majority of the ν_μ flux in the MiniBooNE detector. The total p-Be meson production cross-sections are obtained from the data compiled by the Particle Data Group [10]. A GEANT4 simulation is used to model the BNB beamline geometry and meson transport which includes the Al focusing horn, the target hall, and the 50 meter meson decay volume. The geometry model matches the actual constructed beamline. The Horn magnetic field generated by the 174 kA modeled in GEANT4 includes the skin-depth effect. Tertiary interactions of the hadrons from the target with the beamline material are modeled in GEANT4. The predicted BNB ν_μ interaction rates and the observed rates in MiniBooNE are shown in Figure 6. The shape of the ν_μ event rate in the MiniBooNE detector matches the prediction very well, but an overall normalization factor of 1.21 was required to match the observed absolute event rate. The estimated uncertainties

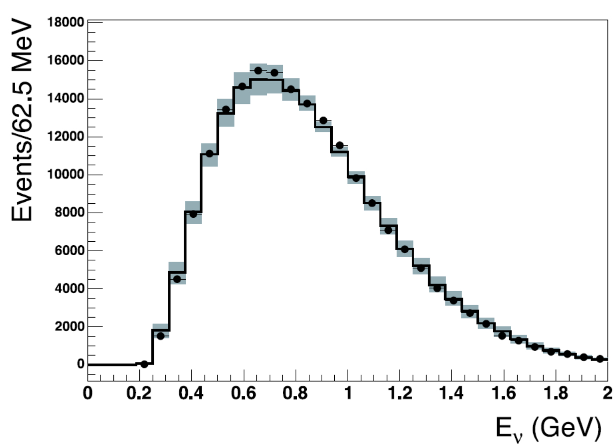


Figure 6: ν_μ event rates from the BNB as observed in the MiniBooNE detector and the tuned MC predictions scaled up by 1.21. The points with error bars are the observed events and the histograms are the MC predictions.

on the BNB ν_μ flux from the proton beam modeling, the p-Be differential production cross-sections, the horn field modeling, and the nucleon and pion total cross-sections are summarized in Table 1. The estimated flux model uncertainties are dominated by the p-Be production cross-sections which are estimated to be 15%.

Source of Uncertainty	MINOS ND	MiniBooNE
Proton delivery	2%	2%
Horn field	8%	2%
Horn material budget	3%	
Target hadro-production	2%	15%
Target degradation	4%	N/A
Nucleon cross-sections		2.8%
Pion cross-sections		1.2%

Table 1: Sources of uncertainty on the ν_μ flux predictions from the NuMI beamline in the MINOS ND and the BNB in the MiniBooNE detector.

3 Flux Predictions and Residual Systematics in 2-Detector Neutrino Oscillation Experiments

The MINOS and T2K experiments are two-detector long-baseline neutrino oscillaton experiments with high precision neutrino oscillation measurements in both disappearance and appearance modes. The neutrino interaction rate in the near detector (ND) is used to predict the unoscillated neutrino rates in the far detector (FD). Since the ND sees an extended source of neutrinos, while the FD sees a point source, the unoscillated neutrino spectrum in both detectors is significantly different [4]. A reliable simulation of the neutrino beamline is therefore needed to extrapolate the ND event rate to the FD. In this section, we will summarize the MINOS measurement of the NuMI flux in the near and far detectors and the extrapolation techniques used to predict the unoscillated flux in the far detector using a near detector.

The NuMI beamline is modeled using a detailed GEANT4 simulation of the as-built geometry. The horn field modeling, and meson transport in the beamline also uses the GEANT4 simulation. The primary 120 GeV p-C interactions in the graphite target as well as tertiary hadron interactions in the beamline material are modeled using the FLUKA 08 simulation [7]. Although the FLUKA 08 hadron production models are tuned to existing measurements, they do not include reliable measurements of p-C and p-Al meson production in the x_F and p_T range of the mesons that contribute to the NuMI neutrino flux in the MINOS detectors. In MINOS, the only data used to tune the beamline simulation to produce a reliable prediction of the unoscillated neutrino rate at the far detector is the observed MINOS ND neutrino interaction rate. The meson differential production from the NuMI target in FLUKA08 as a function of x_F and p_T was parameterized. The parameters of the meson production model, as well as the expected effects from the modeling of the horn currents, skin-depth effects and target and horn misalignments were allowed to vary in a fit of the predicted ND neutrino rate from the simulation to the observed rate. The fit included an overall detector energy scale and offset parameter to account for ND detector mismodeling effects. To better separate detector and beam modeling effects, the NuMI beam tune was varied by changing the target position with respect to the horns and the ν_μ and $\bar{\nu}_\mu$ data from 3 different tunes : low-energy, medium-energy, and high-energy were simultaneously fit [8]. The tuned simulation results and the observed MINOS ND data from two different NuMI beam tunes are shown in Figure 6. The tuned simulation model matches the ND data well. The estimated uncertainties on the ND ν_μ event rate obtained from varying the target hadron production parameterization, the horn field modeling, and the horn material budget is shown in Table 1. In 2008 and 2009, the ND event rate was observed to decline. The effect was best modeled in the FLUKA simulaiton of the target by radiation damage to the NuMI target core [11]. As a result, an uncertainty on the ND event rate due to target degradation is also included in the predicted ND rate uncertainties from the simulation. The uncertainties in the MINOS ND rate thus obtained from the target production and beamline simulation are dominated by the horn field and skin-depth effect uncertainties which are 8%. Variations in the target hadron production parameterized model produced an uncertainty of around 2% in the predicted ND rate. It is worthwhile to note that this technique assumes that the neutrino interaction cross-sections in the MINOS ND simulation are correctly modeled. Since both detectors are iron scintillator sampling calorimeters, the neutrino interaction cross-section uncertainties - which are large in the few GeV range of MINOS - cancel out in the extrapolation of the observed rates from ND to FD. The NuMI beamline simulation tuning technique described here cannot be used as a reliable prediction of the absolute NuMI flux in the ND. The technique is used to improve the modeling of the target hadron production, horn focusing and beamline geometry in the beamline simulation to allow a reliable extrapolation of the observed MINOS ND event rate to the FD. The technique is also used to determine the residual uncertainty from the beamline geometry and hadron production uncertainties in the extrapolation from ND to FD. The dominant beamline modeling uncertainties as a function of the ν_μ energy in the ND are shown in Figure 7. The residual uncertainty on the near to far extrapolation as a function of the neutrino energy in the far detector is also shown in Figure 7. It is significant to note that in a two detector long-baseline oscillation like MINOS, the flux uncertainties do not cancel out entirely since a beamline simulation is still needed to extrapolate from near to far. The largest residual beamline modeling uncertainties on the predicted FD event rate in MINOS are from the horn field effects and are of order $\sim 3\%$.

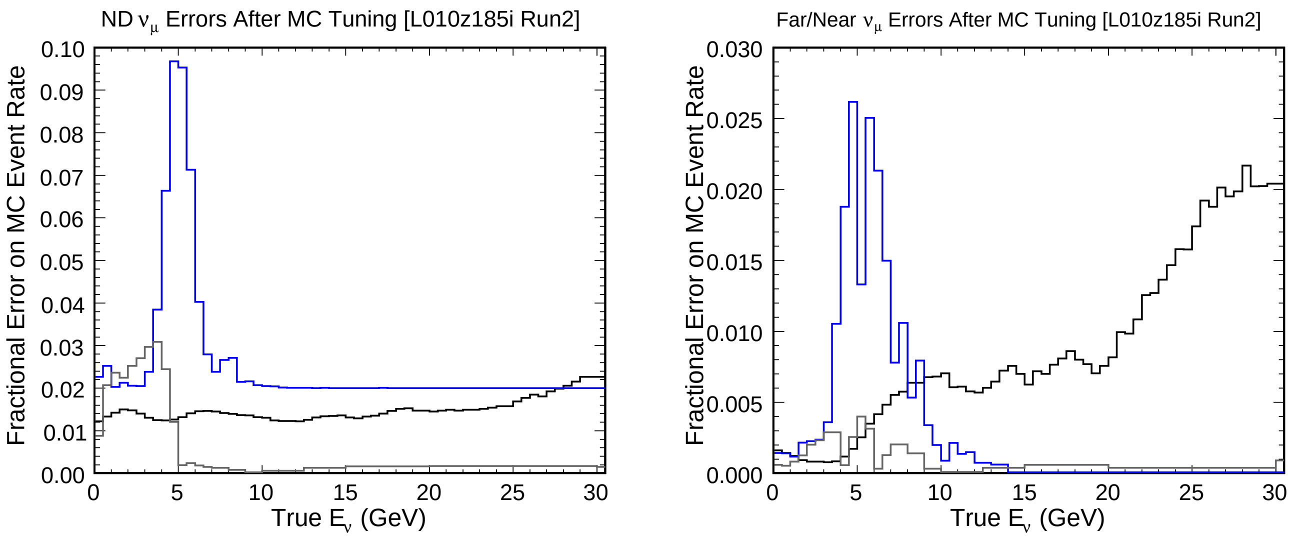


Figure 7: The dominant uncertainties on the MINOS ND neutrino rate predictions (left) obtained from tuning the MC to the observed ND event rate and the residual uncertainties on the Near to Far extrapolation (right). The gray histogram represents the uncertainty from the modeling of the horn material budget. The black histogram is the uncertainty from parameterization of the meson production from the target. The blue histogram is the total uncertainty from the horn field modeling which includes the horn current uncertainty, the skin-depth effect, and the two horn misalignments.

The NuMI beamline simulation tuned to the on-axis MINOS ND was also used to predict the NuMI neutrino flux in MiniBooNE detector which is at a distance of 745m from the NuMI target and 110 mrad off-axis. The NuMI off-axis flux in MiniBooNE covers the same neutrino energy region as the BNB on-axis beam as shown in Figure 5. The NuMI decay region is very long at 675m in length and the MiniBooNE detector sits very close to the beam dump at the end of the decay region. Therefore, the MiniBooNE detector sees a very extended source of off-axis neutrinos from NuMI. The observed NuMI ν_μ and ν_e neutrino interaction rates in MiniBooNE with the preduction from the tuned NuMI beam simulation overlaid [13] are shown in Figure 8. The data and prediction are in very good agreement for both ν_μ and ν_e. The uncertainties on the predicted event rates are shown as a gray band and are dominated by the neutrino cross-section uncertainties. More details on the measurement of the NuMI beam in the MiniBooNE detector can be found in [12] and [13].

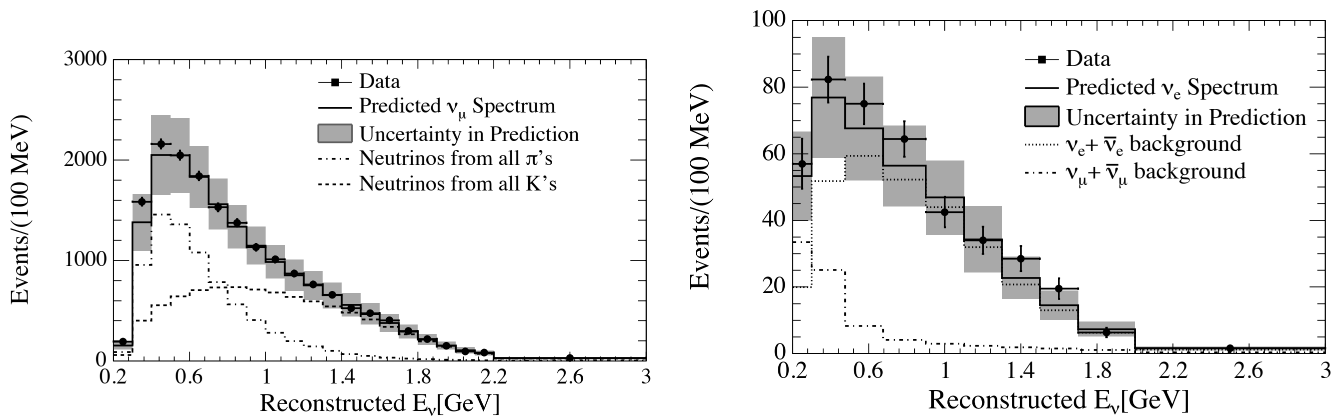


Figure 8: The ν_μ (left) and ν_e (right) event rates from the NuMI beamline as seen in the MiniBooNE detector with the tuned NuMI simulation predictions overlaid as solid lines. The gray bands are the total uncertainties on the predicted event rate including the cross-section uncertainties.

4 SBN Flux and Systematics with Multiple Detectors

The Fermilab SBN program will utilize multiple detectors deployed along the BNB beamline and search for neutrino oscillations in a manner similar to 2-detector long baseline experiments such as MINOS and T2K where a near detector located as close possible to the neutrino source measures the neutrino event rate on the same target material before oscillations. The spectra of ν_μ and ν_e at a far detector (or multiple far detectors) is then compared to the spectrum in the near detector to search for evidence of neutrinos oscillating into new unknown mass states. As discussed in the summary of the MINOS analysis, the near detector sees an extended source of neutrinos whereas the far detectors see a more point like source. This effect results in differences in near and far spectra unrelated to neutrino oscillations. Figure 9 demonstrates the ratio of the spectrum at the proposed SBN-FD (ICARUS T600) located 700m from the BNB and the SBN-ND located a distance of 150m from the neutrino source. As a result

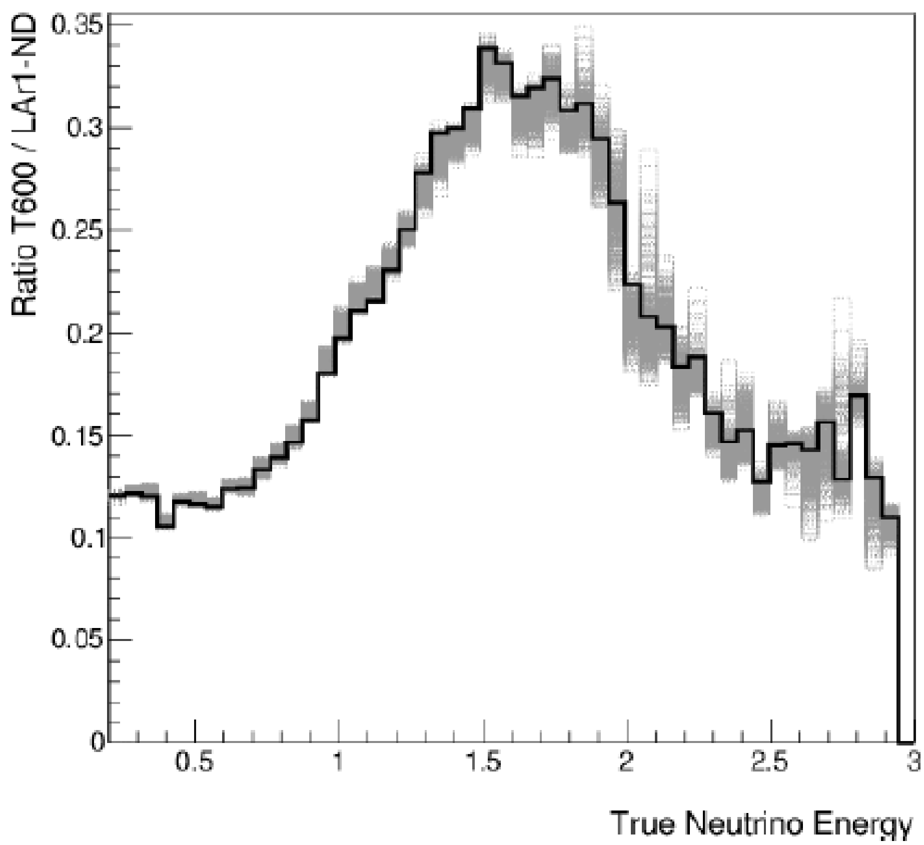


Figure 9: Ratio of the ν_μ spectra at the SBN-FD (T600) located at 700m from the BNB compared to the SBN-ND located at 150m.

of this geometric effect of the beamline, there will always be residual flux uncertainties in the oscillation analysis even with multiple detectors deployed at different L/E so long as the baselines are comparable to the length of the decay region.

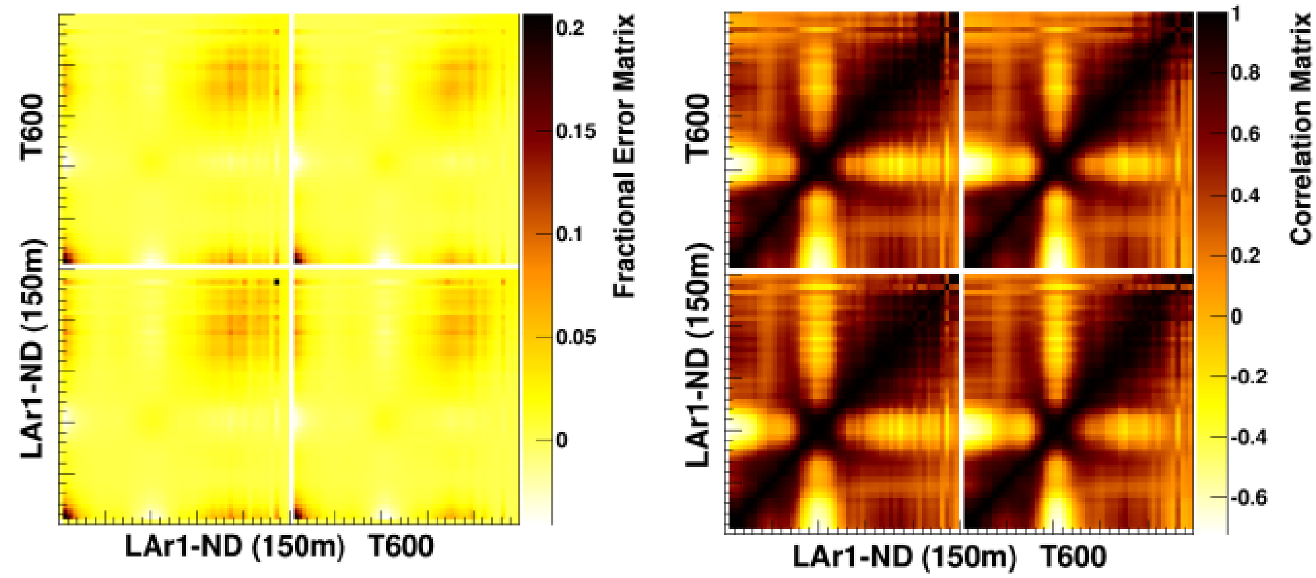


Figure 10: Flux error matrix for an SBN-ND at 150m and the T600 at 700m. The fractional error matrix is shown on the left and the correlation matrix is shown on the right.

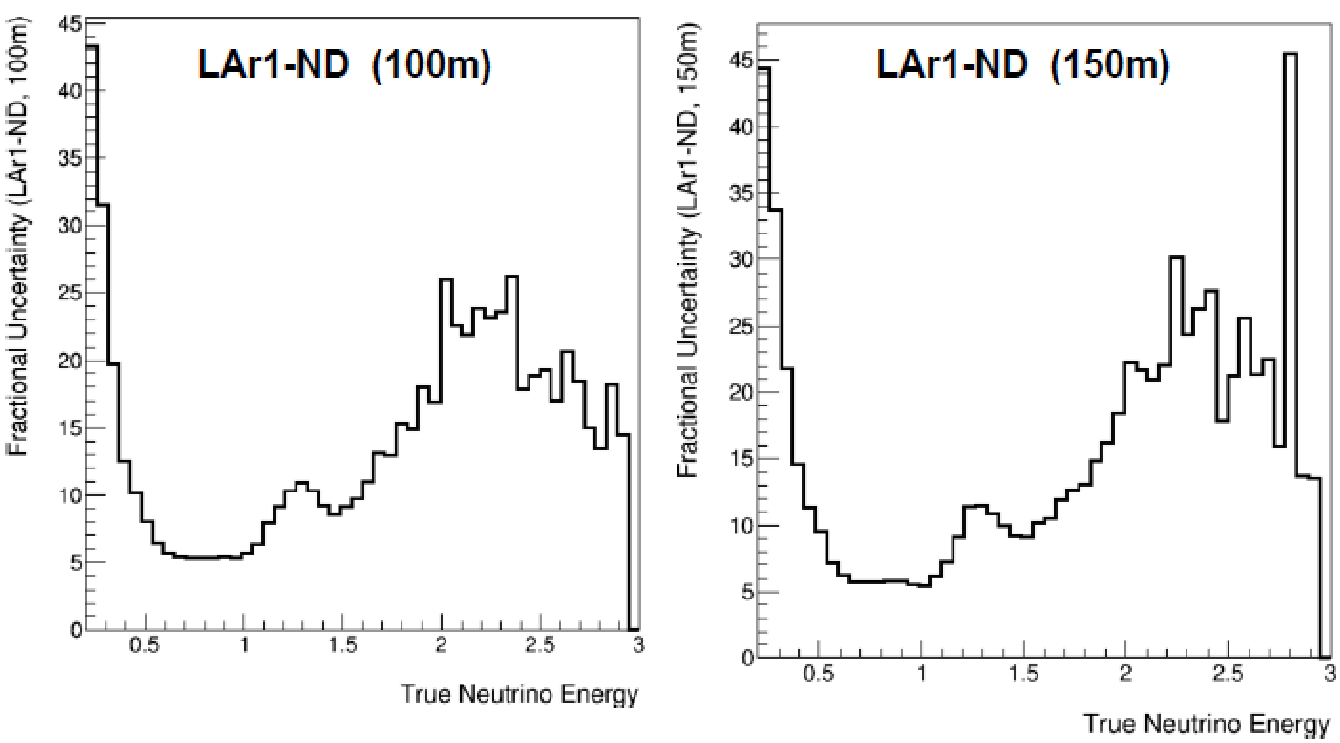


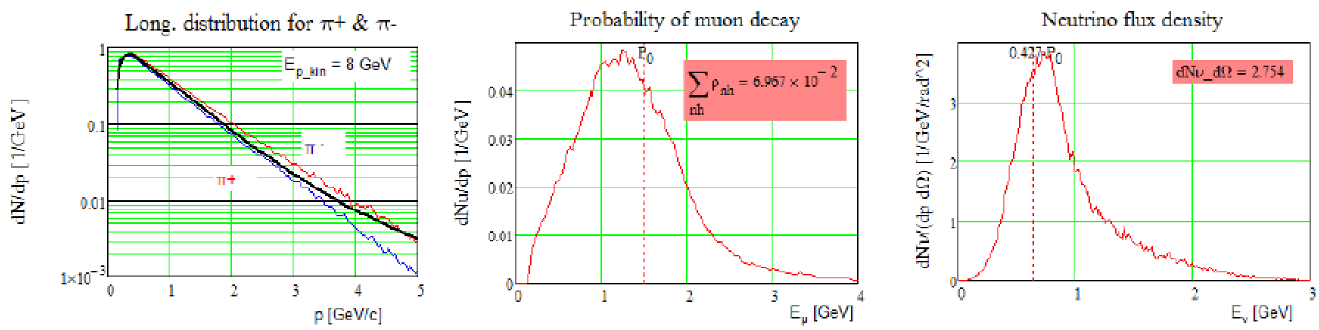
Figure 11: Fractional flux uncertainties along the diagonal of the uncertainty matrix for SBN-ND located at 100m (left) and 150m (right)

5 Impact of Flux Systematics on Oscillation Sensitivities

6 Studies of BNB Upgrades

6.1 Targetry

Beryllium (π^+)



Carbon (π^+)

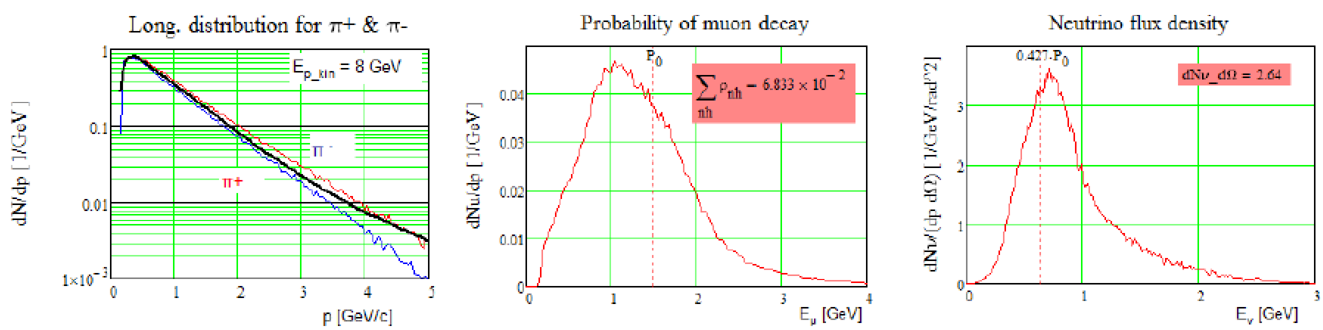
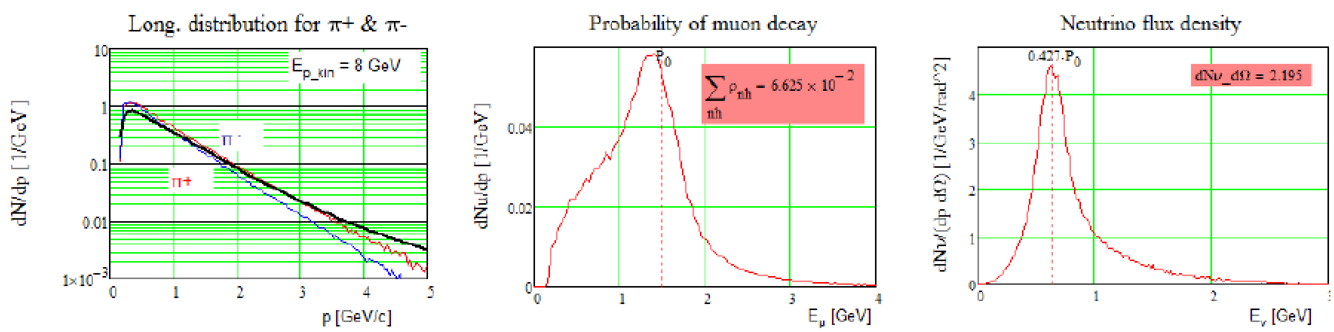


Figure 12: Pion production from different target materials and the impact of the BNB neutrino flux.

Inconel (π^+)



Tungsten (π^+)

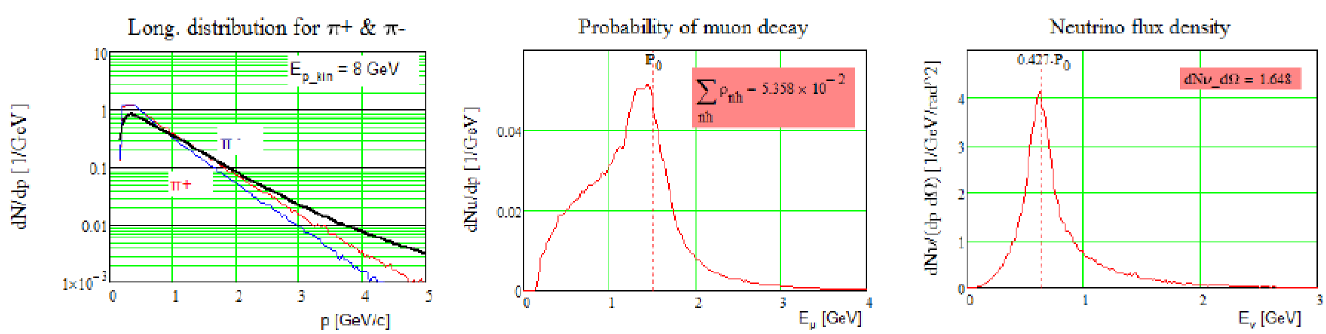


Figure 13: Pion production from different target materials and the impact of the BNB neutrino flux.

6.2 Focusing Systems

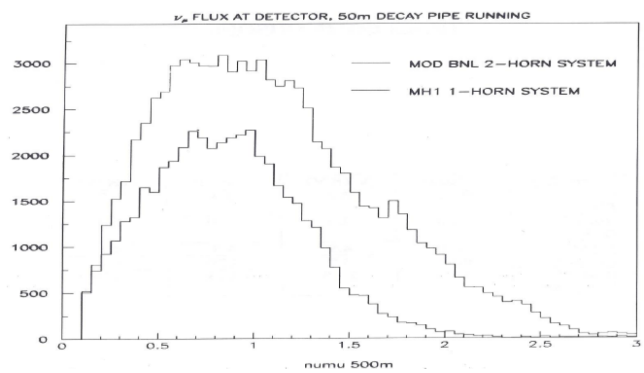


Figure 14: Early studies of the BNB neutrino flux with two BNL style horns

A 0th order approximation of the possible BNB flux with a second horn is shown in Figure 15

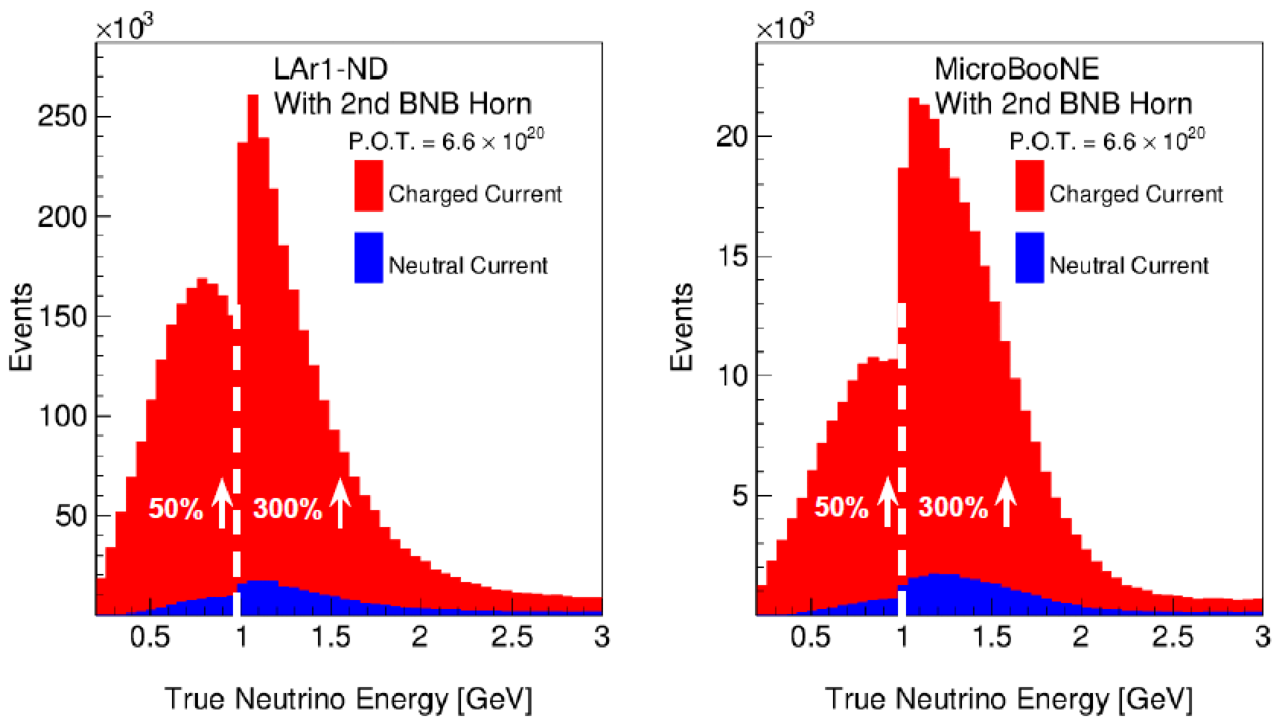


Figure 15: A 0th order approximation of the booster beam flux with a 2nd horn added

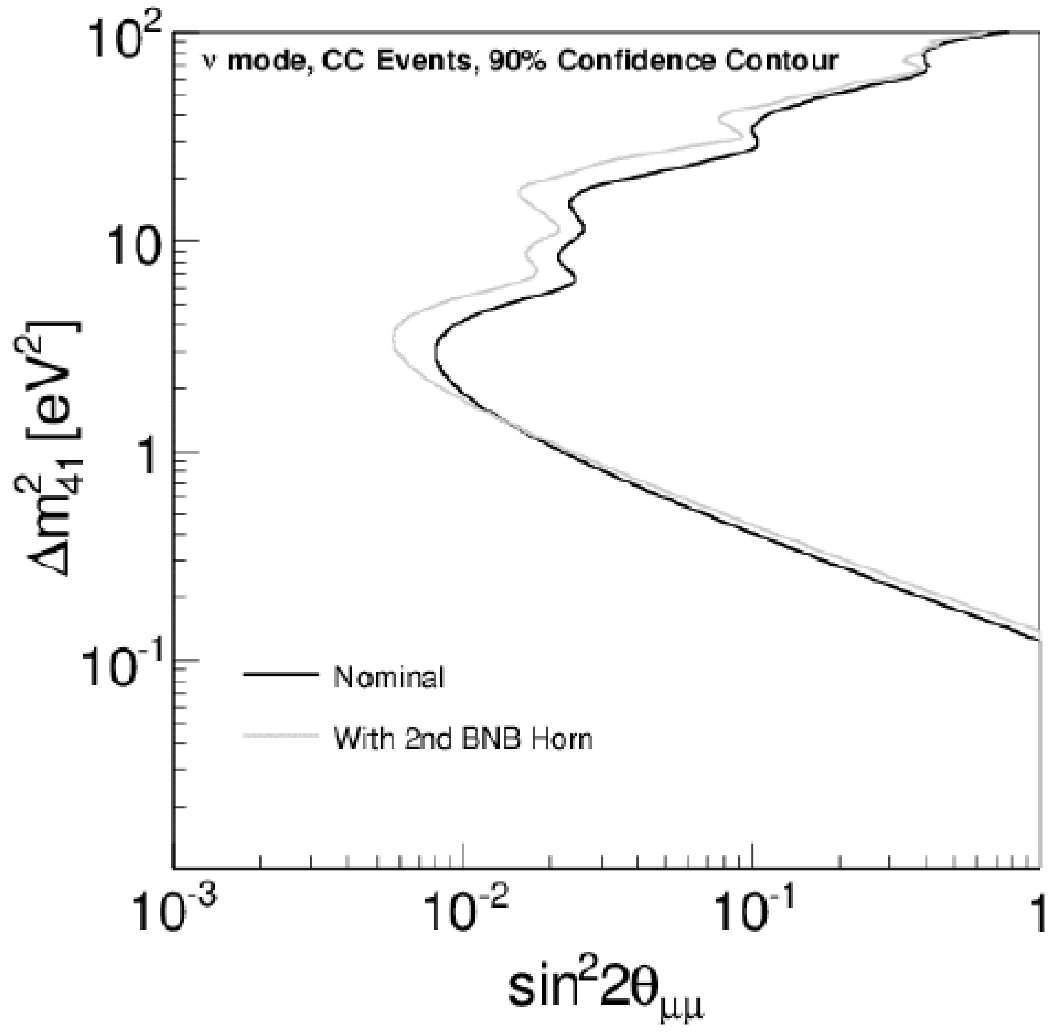


Figure 16: Impact of a 2nd horn on disappearance sensitivity.

7 Conclusion

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